

Operational Procedures for Ramping the LHC

P. Collier AB/OP-LHC
(on behalf of the LHC-OP Team)

Ramp/Squeeze Implementation
Baseline Energy Ramp
Settings Generation
Parameter space for Trimming and Correction
Making a Ramp
 The Normal Cycle
 Decay & Snapback
 Squeezing
Summary

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Ramping the LHC

The two rings of the LHC are tightly coupled by the main dipoles, main quads & inner triplets ...

At 450 GeV the link can almost be ignored and the two rings tuned separately.

Not so the ramp and squeeze.

The two rings are tightly locked together during the ramp/squeeze.

Commissioning strategy must take this into account

Concurrent commissioning of ring 1 and ring 2 ramps

As soon as possible ramp tuning should be done with both beams

Careful analysis of regions where corrections will interfere

Almost everything is x2 ...

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Ramp/Squeeze Implementation

Time dependent functions generated for each hardware entity:

- ★ Points consisting of Absolute value and time relative to ramp start
- ★ Arbitrary time spacing
- ★ Number of points determined by the precision with which to follow a given curve

Hardware Controller is responsible for function generation:

- ★ Same controller for power converters and RF
- ★ Linear Interpolation of supplied points – up to 10k
- ★ Synchronization to 1ms

The start is synchronized using general machine timing events

- ★ Power converters, RF and Beam Dump
- ★ Other equipment may follow – e.g. Instrumentation, Collimators

A separate function controls the squeeze (Procedurally Similar)

- ★ No time constraint between end of ramp and start of squeeze

Real time channel – up to 50 Hz corrections

- ★ Use for on-line corrections, feedback etc.

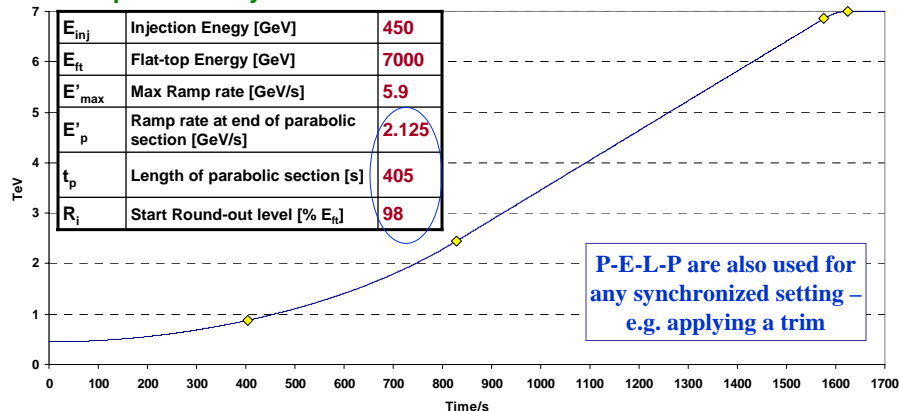
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The Baseline Energy Ramp (Parabolic-Exponential-Linear-Parabolic)

- Minimize voltage discontinuities start with $dI/dt = 0$
- Minimize dynamic errors
- Snapback slowly - takes around 70 seconds

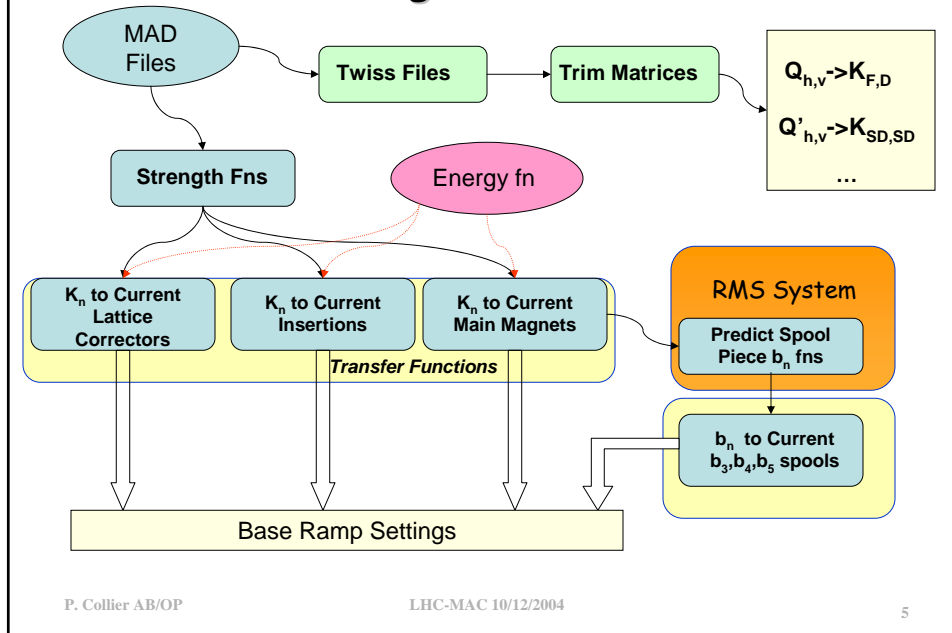


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Settings Generation



Settings Generation (Magnets)

Start with:

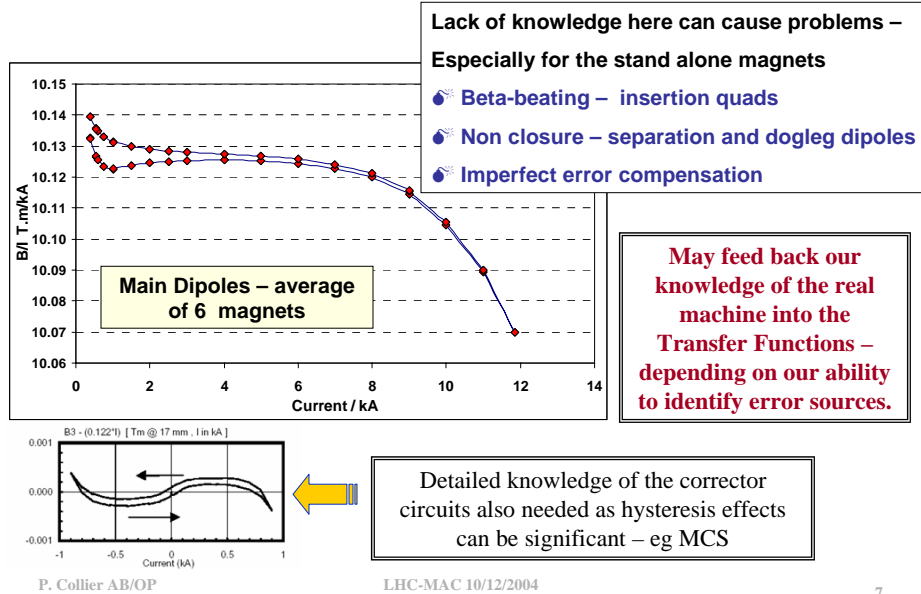
- * Baseline Energy ramp $\rightarrow E(t)$
- * Normalized strengths from MAD – optics files $\rightarrow K(t)$
- * Description of magnet / magnet family e.g. magnetic length

Convert Strength to integrated field $\rightarrow B_n(t)$

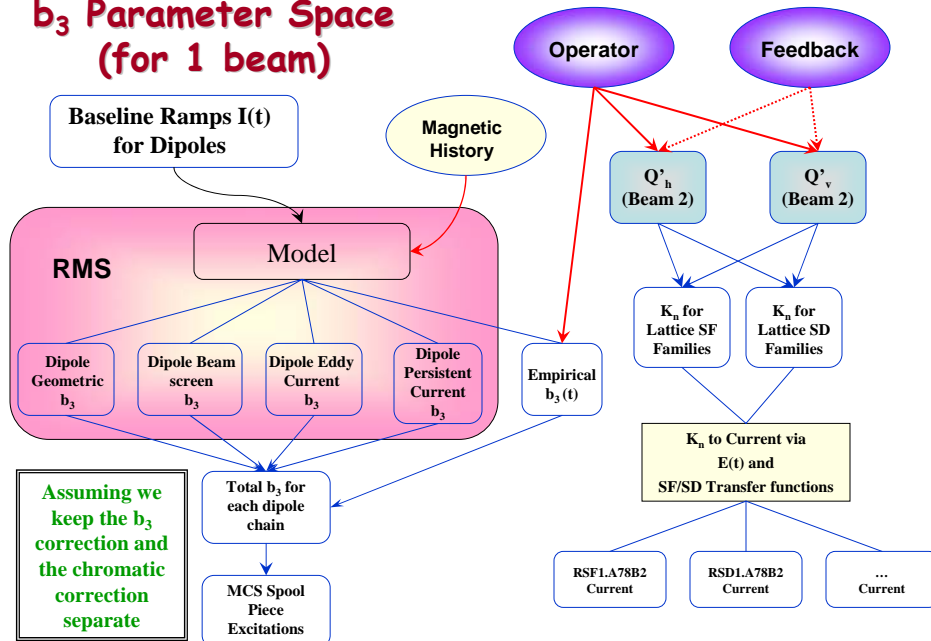
Convert to Current via a transfer function ... $\rightarrow I(t)$

- * TF comes from magnetic measurements : warm & cold
- * Represents the average of many magnets – or just one
- * Need to interpolate between measured points of the transfer function - or are provided with a model
- * The TF information is 'static' and will be stored in the control system for speed of access
- * The RMS is invoked during settings generation when model predictions are required

Transfer Functions



b_3 Parameter Space (for 1 beam)



Ramp/Squeeze functions for Other Elements

RF System –

✳ Will use the same function controllers as the PC's

✳ Requires various functions

- ↳ Frequency
- ↳ Voltage and phase per cavity (x8 per beam)
- ↳ Low-level beam control, synchro loops etc.
- ↳ Radial loop (for commissioning the ramp)
- ↳ Transverse feedback gains etc.

Beam Dump -

✳ Load with the reference energy ramp

- ↳ Will work out the septum, MKD, MKB functions for itself.
- ↳ Will track the energy using a hardware 'energy meter'

Others – Instrumentation, Collimators etc

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Additions to the base ramp

Additional Elements for the base ramp will be added from various sources:

- ↳ Separation and Crossing angle schemes
- ↳ Experimental magnet compensation schemes
- ↳ Coupling compensation
- ↳ Octupoles
- ↳ Inner triplet corrections
- ↳ Standard trims – from experience – e.g.
 - Optics tweaks for example to reduce beta-beating
 - Compensate for b_2 (inner) = - b_2 (outer)
 - Pre-set tune, chromaticity, coupling, trims ...



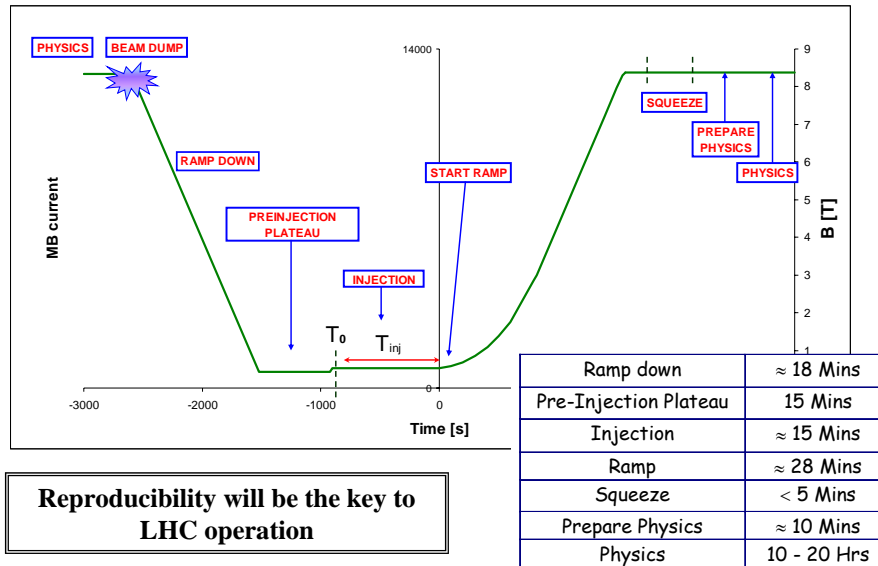
Ramp is ready to put on the machine and commission with beam

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The Nominal Cycle



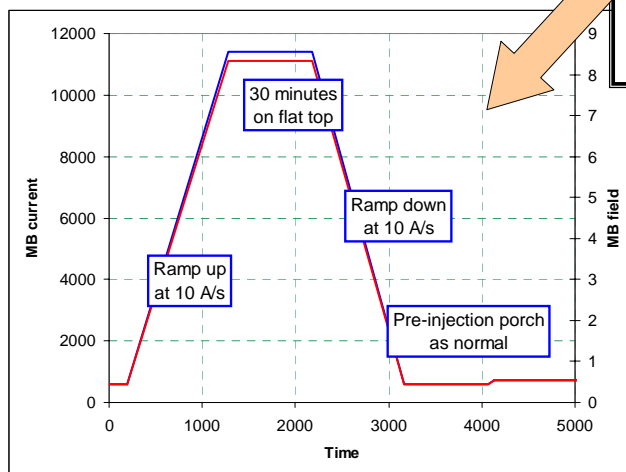
Reproducibility will be the key to LHC operation

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OP Magnetic Re-Cycle



Needed after switching ON,
After a quench,
Or whenever we find the reproducibility is insufficient.

Ramp down

Main bends at 10 A/s
Quads 'freewheel'

Cycle ALL other circuits looking for reproducible conditions at injection

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Operational Variations: fill-to-fill

- * The flat top energy
- * The time at flat top
- * The pre-injection plateau length
- * Length of time at injection
- * Stop with beam in the ramp
- * Machine development
- * Operational modes (for example TOTEM, Pb⁸²⁺)
- * Commissioning & setup periods
- * Access, Quenches, problems, faults etc...

All may contribute to a lack of reproducibility

Dynamic Effects

- Beam parameters, dynamic aperture within very tight tolerances
- Have to be able to cope with inevitable run-to-run variations – large effects
- Tight limits on correction of multipole errors
- Not to forget: Corrector behavior – hysteresis effects

Have to correct for:

- ↪ Irreproducibility of the initial conditions – cycle history etc
- ↪ The b_1 , b_2 , a_2 , b_3 ... persistent current decay on the injection plateau
- ↪ Snapback

The required adjustments will be established Using

1. Beam based run-to-run feedforward [& reproducibility]
2. Beam based feedback [difficult in some cases] not initially available
3. RMS:
 - off-line model
 - powering history dependent model
 - feed-forward from reference magnet measurements

Pre-Injection Plateau

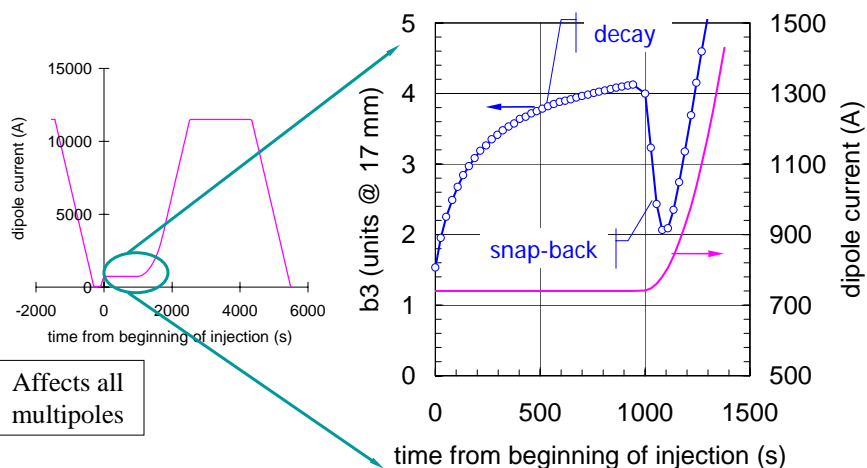
- * Check and prepare everything
 - kickers, beam dump,
 - Machine protection elements,
 - collimators, instrumentation, etc.
 - Injectors and transfer lines
 - Beam permit
- * Can have a variable length:
 - Aim for 5 to 15 minutes ... but
 - May have to give access during this time.
- * Ramp using a PELP to injection level for all circuits
- * Start the clock

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Decay & Snapback: The Problem



Affects all
multipoles

Parameter	Nominal tolerance	Limit on $b_n(\text{MB}) - \text{Inj.}$	Approx. Decay	Parameter swing
Q'	$Q' \approx 2 \quad \Delta Q' \approx \pm 1$	± 0.02	1.7	$\Delta Q' \approx +71/-64$

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Injection Plateau – before & After Beam

- * As soon as we arrive at injection level the persistent currents start to decay...
- * Start **tracking and correcting for drifts in b_1 , b_2 and b_3** (at least)
 - ↳ Either via a model prediction from the RMS system, or direct feedback from reference measurements (or both)
 - ↳ With beam in the machine direct feedback becomes possible.
 - ↳ Corrections applied via the real-time channel on the PC's
- * To **keep energy constant** the horizontal orbit correctors will be driven to compensate the b_1 drift.

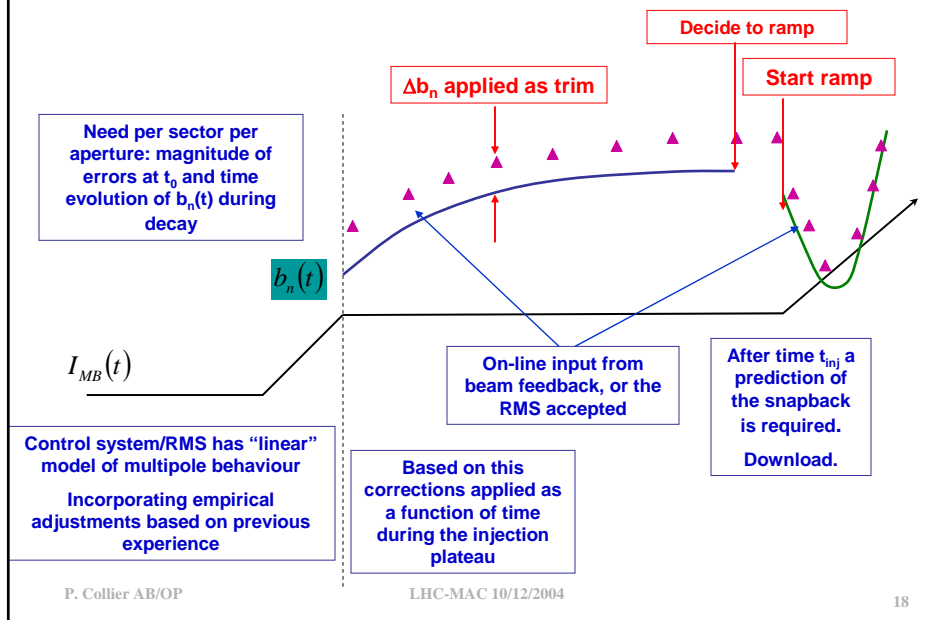
The better our knowledge of the magnetic machine, the less we will have to rely on direct feedback

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Dynamic effects - correction



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Snapback – (example Q')

★ Just before ramping:

- ↳ Extract total b_3 correction (at time of ramp) from slow Q' measurements & b_3 corrections during injection
- ↳ Invoke fit for snapback prediction
- ↳ Convert to currents in the b_3 spool piece circuits
- ↳ Incorporate into the ramp functions & download
- ↳ Remove Injection protection devices ...inhibit injection
- ↳ Collimators probably do not move for the ramp

★ Functions invoked at ramp start by standard timing event

- ↳ Ramp starts slowly – 9 GeV in the first minute

★ Feed-forward from RMS measurements to the next cycle would help refine the prediction of the snapback

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Beam Based Measurements & Feedback

The more we can predict the behavior the less we shall rely on beam based feedback to reach the required tolerances.

Orbit feedback needed early on

- ↳ Stabilize the beam in the beam dump and collimation regions
- ↳ Provide decay/snapback correction for the main dipoles
- ↳ Global orbit might initially be feed-forward to allow more careful analysis before incorporation of orbit trims.

Tune History measurements will be needed right from the start.

- ↳ Must be possible with pilot bunches
- ↳ Feed-forward to correct the tune
- ↳ Measure with a frequency modulation to correct Q' – or head-tail
- ↳ Closing the feedback loop for tune will take time ...

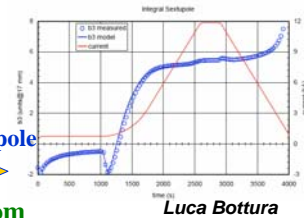
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Beyond Snapback

- ★ Life Should get better once the snapback is over
 - ✦ Although the variation of the b_3 component in the dipole continues to be high until ~ 4.5 TeV.
- ★ Most corrections will be done using feed-forward from measurements made 'on-the-fly'
 - ✦ Incorporation of the trims into the ramp will require careful analysis to identify source
 - ✦ Important to apply corrections locally as much as possible
- ★ May have to stop with beam in the ramp – use timing event:
 - ✦ Implies the need for: control of round-off behaviour & decay after the stop
 - ✦ For use during commissioning for detailed measurements & correction, check of beam dump etc.
 - ✦ Re-start with beam not envisaged (at least initially).
- ★ The ramp stops naturally when the functions come to an end.



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Early Ramp Commissioning

Initial Machine setup at 450 GeV will use a cycle with a 'degauss blip' →

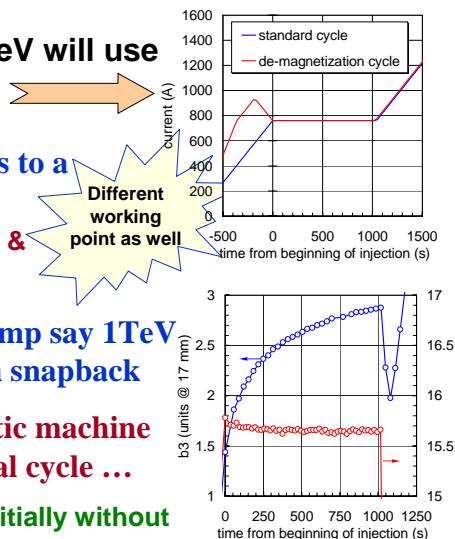
Will have to transfer all our trims to a ramping cycle

Transfer of 450 GeV corrections & Incorporation into the ramp

May start with a lower energy ramp say 1TeV to save time while we get through snapback

But this will mean the magnetic machine changes in going to full normal cycle ...

Beam 1, Beam 2 then Both – but initially without Crossing angle



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The Squeeze

- ★ Procedurally very similar to the ramp
- ★ Will exist as a separate set of absolute functions
 - ↳ Changes to the end of the ramp will propagate into the squeeze
- ★ Will probably squeeze one IP after another.
 - ↳ Allows us to separate out effects and error sources
 - ↳ May maintain squeeze files with other options ...
- ★ Will involve a good fraction of the machine:
 - ↳ The four experimental insertions,
 - ↳ The lattice quads and correctors
- ★ Collimators must be moved to protect the aperture.
 - ↳ Either load a file before starting, or
 - ↳ Load one, or more, files during, or
 - ↳ The collimators follow a continuous function

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Early Squeeze Commissioning

- ※ Start pilot physics un-squeezed (and no X-ing angle)
- ※ Commission first to an intermediate β^* :
 - ↳ Around 2m. Beyond this point the complications grow...
 - ↳ With no crossing angle – that will get added on later.
 - ↳ Commission squeeze one IR after another – then all together?
- ※ Will need several intermediate optics (11-2 m) in each IR.
- ※ Must be capable at stopping at any point – round-out
 - ↳ In this case will need the possibility to start again with beam
- ※ Considering what form to impose (PELP, PLP etc) on the squeeze
 - ↳ to minimize voltage discontinuity, dynamic errors etc ...
- ※ Tune History and orbit feedback will be needed to survive
 - ↳ Feed-forward the main basis for progress.
 - ↳ Hopefully good reproducibility at high energy

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Summary

Ramp and Squeeze are procedurally very similar

- Based on downloaded functions containing an arbitrary number of points
- Interpolation in the front end function controllers
- Same controllers for PC's and RF.
- Synchronized by general timing event

The basis for generating a working ramp has been sketched out

- Generating the base functions
- Applying corrections
- Commissioning the ramp and surviving snapback
- Many details remain to be treated – mainly as part of the control system

Surviving the ramp in the LHC is based on:

- Good knowledge of the magnetic machine – and predictive power
- Generating a reproducible cycle –
 - allows feeding back from previous cycles and prediction of dynamic effects
- Beam based measurements & feedback to mop up the remainder.